Theory Overview of Chiral Magnetic Effect in Heavy-Ion Collisions

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June 8, 2016

RHIC/AGS Users Meeting, BNL, June 7-10, 2016

(Acknowledgment: CME Task Force Meeting)

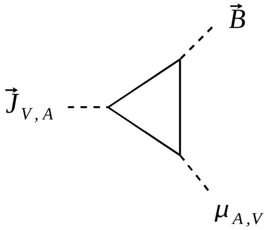
Plan of the talk

- A question: **Is the Chiral Magnetic Wave (CMW) something different from the Chiral Magnetic Effect (CME)?**
- Issues of CME in heavy-ion collisions
  - Issues of CME itself
  - Issues related to heavy-ion collision
  - Issues related to other backgrounds of the proposed observables
- What do we need to do?

Chiral Magnetic Effect (CME) and Chiral Separation Effect (CSE)

(Fukushima-Kharzeev-Warringa, Son-Zhitnitsky, Vilenkin)

$$\vec{J}_V = \frac{eN_c}{2\pi^2}\mu_A \vec{B}\,, \quad \vec{J}_A = \frac{eN_c}{2\pi^2}\mu_V \vec{B}$$



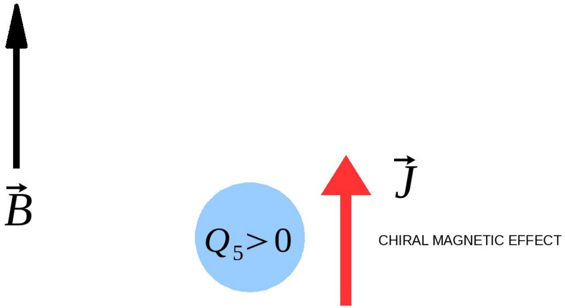
Note the $< AVV >$ structure

Q: Is the Chiral Magnetic Wave (CMW) something different from the Chiral Magnetic Effect (CME)?

A: CME+CSE+Hydrodynamics = CMW

CMW is the inclusive universal language of CME/CSE in hydrodynamics

Why do we have waves ?



$$\vec{J}_V = \frac{N_c e\vec{B}}{2\pi^2}\mu_A \quad , \quad \vec{J}_A = \frac{N_c e\vec{B}}{2\pi^2}\mu_V$$

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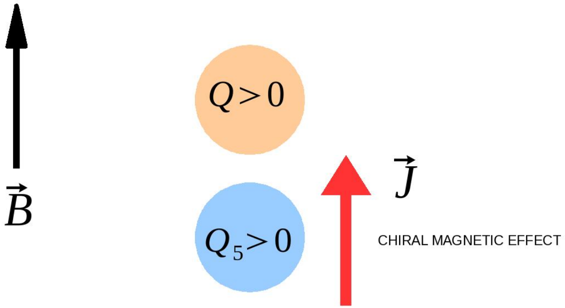

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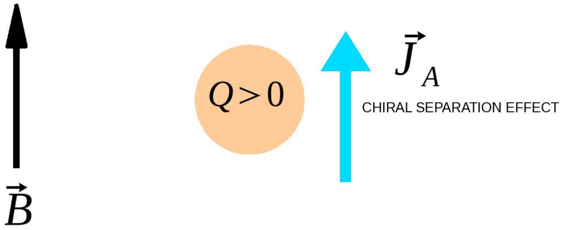

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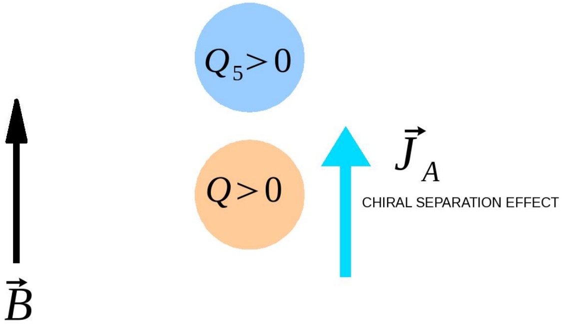

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CMW: Sound Waves of Chiral Charges
(Kharzeev-HUY)

Add and subtract CME and CSE to go to
Left/Right-handed chiralities

$$\vec{J}_V = \frac{eN_c}{2\pi^2}\mu_A \vec{B}\,, \quad \vec{J}_A = \frac{eN_c}{2\pi^2}\mu_V \vec{B}$$

$$J_{R/L} \equiv \frac{1}{2}(J_V \pm J_A)$$

Then, we have a "diagonalization" of the CME/CSE

$$\vec{J}_R = \frac{eN_c}{4\pi^2}\mu_R \vec{B}\,, \quad \vec{J}_L = -\frac{eN_c}{4\pi^2}\mu_L \vec{B}\,, \quad \mu_{L/R} \approx \frac{1}{\alpha} n_{L/R}$$

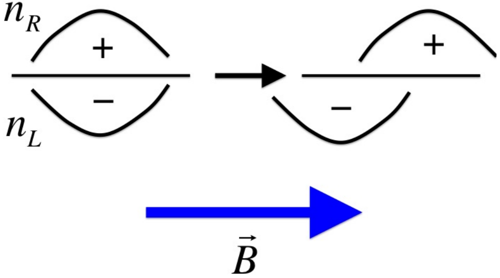
Hydro charge conservation $\partial_\mu J^\mu_{L/R} = 0$ gives

$$\left(\partial_t + \vec{v}_\chi \cdot \vec{\nabla}\right) n_R = 0\,, \left(\partial_t - \vec{v}_\chi \cdot \vec{\nabla}\right) n_L = 0\,, \vec{v}_\chi = \frac{eN_c}{4\pi^2\alpha}\vec{B}$$

Two Independent Uni-directional Propagating Waves !

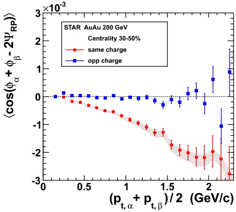
Development of a charge dipole from initial axial charge

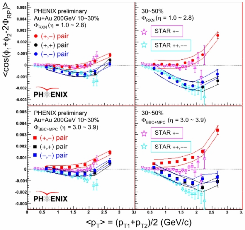
$$n_A > 0\,,\quad n_V = 0 \longrightarrow n_R = \frac{1}{2}n_A\,,\quad n_L = -\frac{1}{2}n_A = -n_R$$

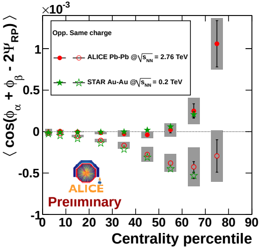


Charge Dipole Probe in RHIC and LHC

$$< cos(\phi_1 + \phi_2 - 2\Psi_{RP}) >$$

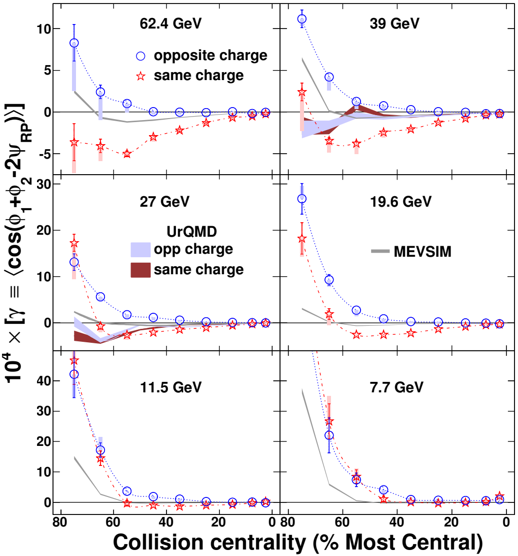






Beam Energy Scan

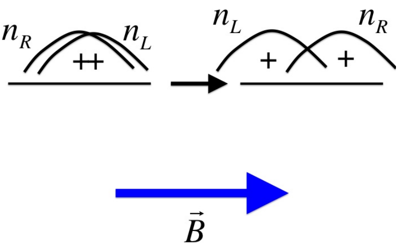
(Phys.Rev.Lett. 113 (2014) 052302)



Development of a charge quadrupole from initial electric charge

(Burnier-Kharzeev-Liao-HUY, Gorba-Miransky-Shovkovy)

$$n_A = 0\,, \quad n_V > 0 \longrightarrow n_R = \frac{1}{2} n_V\,, \quad n_L = \frac{1}{2} n_V = n_R$$

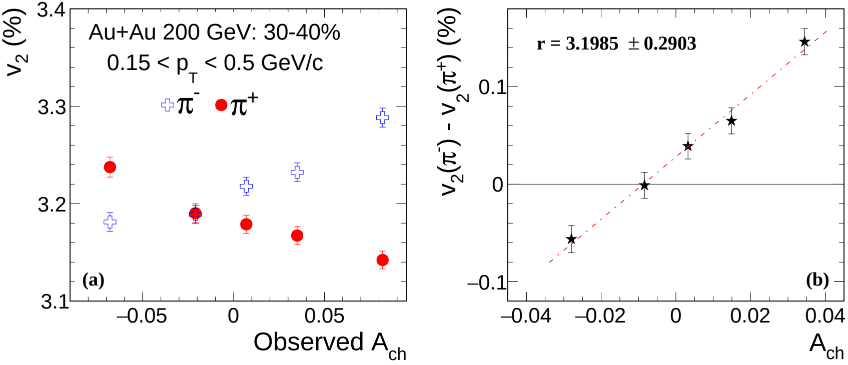


Prediction:

$v_2(\pi^-) - v_2(\pi^+) = r\ Q_{init}$ **with the slope** $r > 0$

Linear dependency check

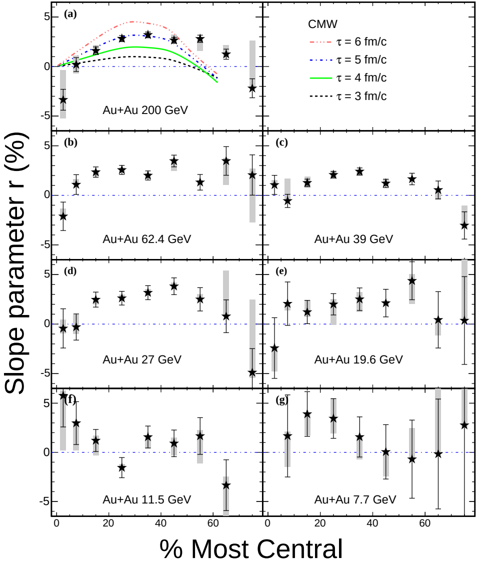
(**Phys.Rev.Lett. 114 (2015) 25, 252302**)



$\Delta v_2 = r\ A_\pm + \Delta v_2^0$: **Note the intercept** Δv_2^0 **(Stephanov-HUY)**

Beam energy Scan

(Phys.Rev.Lett. 114 (2015) 25, 252302)



A reasonable expectation is:

What should be happening is a mixture of dipole and quadrupole

CMW is the universal language for both phenomena

Four Commonly Raised Issues in CME

- **Q:** Axial charge is not conserved. Does CME make sense?
- **Q:** Electromagnetic fields are dynamical. Should't we solve the Maxwell equations with CME?
- **Q:** Magnetic field is rapidly changing in time. Does CME remain the same?
- **Q:** How much do we know about CME in the early pre-equilibrium phase of the QGP?

Q: Axial charge is not conserved

Conservation law is modified to $\partial_\mu J_A^\mu = -\frac{1}{\tau_R} n_A$ where the relaxation rate is given by

$$\frac{1}{\tau_R} \sim \alpha_s^5 \log(1/\alpha_s) T + \alpha_s m_q^2 / T$$

The CMW dispersion relation becomes (Stephanov-HUY-Yin)

$$\omega = -\frac{i}{2\tau_s} \pm \sqrt{-\frac{1}{4\tau_s^2} + v_\chi^2 k^2}$$

A transition from CMW ($k \gg 1/\tau_R$) to pure diffusion ($k \ll 1/\tau_R$)

τ_R is numerically larger than 10 fm with $\alpha_s = 0.2$ and $m_q = 10$ MeV

It is okay to neglect this in heavy-ion collisions

Q: Electromagnetic field is dynamical

Longitudinal Mode:

The CMW dispersion becomes (Kharzeev-HUY)

$$\omega^2 = v_\chi^2 k^2 + m_B^2$$

where

$$v_\chi = \frac{eN_c}{2\pi^2\alpha} B\,, \quad m_B \equiv \frac{e^2 N_c}{2\pi^2\sqrt{\alpha}} B$$

CMW becomes "massive"

Numerically, $m_B^{-1} \approx 20$ fm with $eB \sim m_\pi^2$ and $T \approx 200$ MeV, the basic reason is the smallness of α_{EM}

It is okay to neglect this in heavy-ion collisions

Q: Electromagnetic field is dynamical

Transverse Mode:

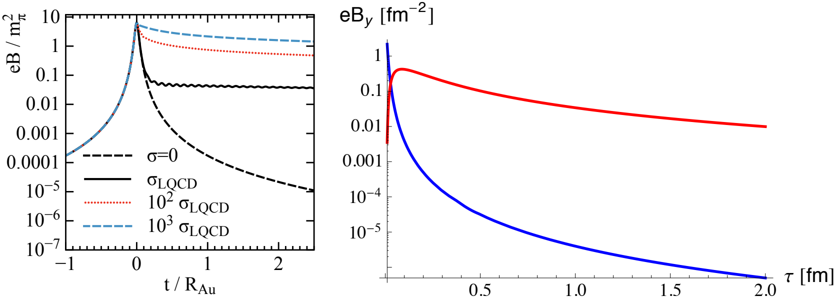
Transverse modes become helicity-polarized via the transition from the fermion helicity (axial charge) into the magnetic helicity. For low enough k, the resulting chiral magneto-hydrodynamics features inverse cascades with turbulence (eg. a recent work by Hirono-Kharzeev-Yin and Yamamoto).

Due to the smallness of α_{EM} and μ_A/T, the space-time scale $k \sim \alpha_{EM}\mu_A$ is numerically much larger than 10 fm

It is okay to neglect this in heavy-ion collisions, unless $\mu_A/T \sim 1/\alpha_{EM} \sim 100$

Q: Magnetic field is rapidly changing

Magnetic field in QGP medium



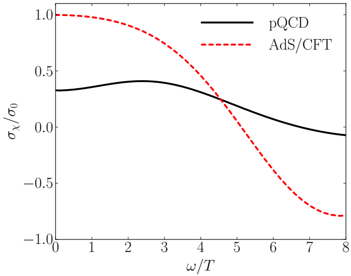
(Tuchin, McLerran-Skokov, Gursoy-Kharzeev-Rajagopal)

Faraday Effect with equilibrium QGP conductivity, which can be questioned

CME in the time-changing magnetic field

In frequency space,

$$\vec{J}(\omega) = \sigma_\chi(\omega)\vec{B}(\omega)$$



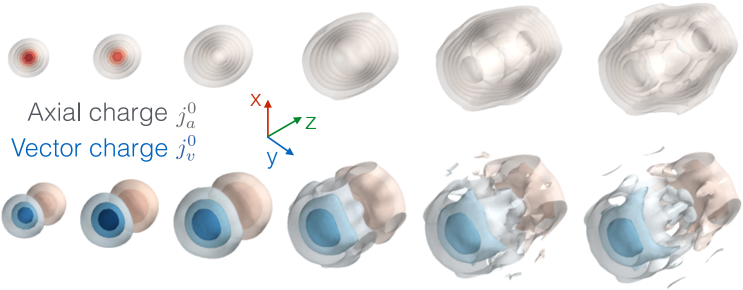
(Kharzeev-Warringa, HUY, Jimenez-HUY)

$$\sigma_\chi^{\mathrm{pQCD}}(\omega) \approx \sigma_0 \left(1 - \frac{2}{3}\frac{\omega}{\omega + i\tau_R^{-1}}\right) , \quad \tau_R^{-1} \approx \frac{1}{36} g^4 \log(1/g) T$$

Q: CME/CMW in Pre-Equilibrium

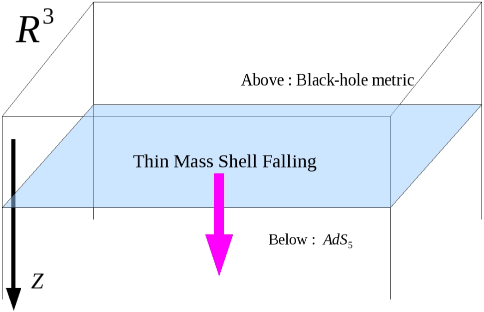
A: We don't know well enough

Recent real-time lattice simulation:
(Mueller-Schlichting-Sharma)



AdS/CFT: (Lin-HUY)

(Initial) Thermalization (2) : Falling Mass Shell



(Lin-Shuryak)

Dispersion Relation

$$\omega = \sqrt{f(z_s)}k + \Delta\omega$$

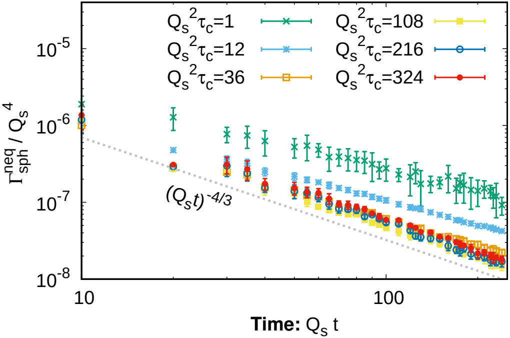
where z_s is the holographic location of the mass shell, and $f(z_s) \approx 1$ initially and $f(z_s) \to 0$ when $z_s \to z_H$ (horizon)

$\Delta\omega$ features characteristics of CMW, and CMW velocity is enhanced by $\sqrt{f(z_s)}$

$$v_\chi^{\mathrm{PreEq}} = \sqrt{f(z_s)} + v_\chi^{\mathrm{Eq}}, \quad v_\chi^{\mathrm{Eq}} \equiv \frac{\partial\Delta\omega}{\partial k}$$

In addition: The amount of initial axial charge is difficult to compute

Recent Glasma simulation: (Mace-Schlichting-Venugopalan)



Other background effects to the charge dipole and quadrupole observables exist, and are sizable

For the charge dipole observable: Local charge conservation and transverse momentum conservation give additional correlations to the two particles (Pratt-Schlichting, Bzdak-Koch-Liao)

For the charge quadrupole observable: Iso-spin transports and viscous corrections give additional contribution to the slope parameter r (Dunlop-Lisa-Sorensen, Hatta-Monnai-Xiao)

Q: What should be done next ?

- Devise a way to understand the pre-equilibrium axial dynamics and CME:
  - Interpolate between real-time AdS/CFT and real-time lattice simulations
  - Simulate Vlasov-Wong equation with Chiral Kinetic Theory (Son-Yamamoto, Stephanov-Yin) in the Glasma
- Run realistic anomalous hydro simulations including all possible background effects (the talk by Yuji Hirono):
  It is planned in the Beam Energy Scan Theory (BEST) topical collaboration

Thank you very much for listening